The Determination of Cloud Altitudes Using SCIAMACHY Onboard ENVISAT

A. A. Kokhanovsky, V. V. Rozanov, W. von Hoyningen-Huene, H. Bovensmann, J. P. Burrows, and H. Klein Baltink

***Abstract*—This letter shows first results for the application of a recently developed semianalytical cloud retrieval algorithm for the determination of cloud top heights from space. The technique is based on the measurements of the top-of-atmosphere reflectance in the oxygen A-band. The depth of the band depends on the cloud top height and its geometrical thickness. The data obtained are compared to ground-based measurements of the cloud top height using a cloud-profiling radar.**

***Index Terms*—Clouds, Environmental Satellite (ENVISAT), radiative transfer, remote sensing.**

I. Introduction

THE SPECTROMETER for Atmospheric Chartography (SCIAMACHY) onboard the Environmental Satellite (ENVISAT) [1] measures the top-of-atmosphere (TOA) reflectance in approximately 8000 spectral points in the spectral range 240–2380 nm. The spatial resolution of the instrument varies depending on the spectral interval. It is 30×60 km^2 for all pixels studied in this letter.

The large size of SCIAMACHY pixels leads to difficulty in the selection of cloud-free pixels. Most of the SCIAMACHY pixels are contaminated by clouds. This can lead to errors in the trace gas retrievals from space using SCIAMACHY and also some other instruments with a poor spatial resolution (e.g., the Global Ozone Monitoring Experiment (GOME) [2]).

The fast retrieval scheme for clouds from the oxygen A-band (FRESCO) algorithm [4] has been developed for use with GOME and SCIAMACHY data and aims to provide improved cloud data products compared with the initial cloud fitting algorithm [8]. It has been well validated and compared to International Satellite Cloud Climatology Project data [5]. FRESCO is based on radiative transfer calculations in the oxygen A-band [14]. The spectral TOA reflectance has a deep minimum close to wavelength $\lambda = 760$ nm due to the oxygen absorption [12]. This minimum is almost undetectable for high clouds, as they strongly reflect photons. Therefore, photons hardly penetrate a cloud. The chance for photons to be absorbed by oxygen beneath the cloud is reduced considerably for high clouds. Therefore, the depth of the minimum can be used for the cloud top height determination [13]. FRESCO in its current form makes a number of assumptions, which yield a fast and reliable algorithm, but limit the accuracy of the retrieved data products. For example, the radiative transfer within the cloud is neglected, and the cloud top is assumed to be a perfect Lambertian reflector. This leads to biases in the retrieved cloud products [10], [11].

Cloud altitude and geometrical thickness are important parameters for a number of meteorological and climatological applications. For instance, the very position of a cloud may be an indication of an inversion layer in the atmosphere. Cloud altitudes and types indicate the thermodynamic and hydrodynamic structure of the atmosphere. These parameters affect energy budgets and radiative heating.

The distribution of heating in the cloud, which is influenced by the cloud top height and the geometrical thickness, is of importance for the cloud dynamics and the evolution of cloud microstructure. Furthermore, cloud top and cloud base heights influence photon horizontal transport in clouds. This effect is important for a number of issues and in particular for a so-called cloud absorption anomaly problem.

This letter aims to verify the the newly developed semi-analytical cloud retrieval algorithm (SACURA) [6], [7], [10], [11] using data from the BBC-2 field campaign (see http://www.knmi.nl/samenw/bbc2). For this, we derive the cloud top height using data from the SCIAMACHY onboard ENVISAT.

The SACURA fully accounts for the radiative transfer in a cloudy medium in the oxygen molecular bands. As a consequence of the improved physical description of radiative transfer within the atmosphere by SACURA, it represents a significant and timely improvement on the FRESCO, which is currently considered to be one of the the best cloud parameter retrieval algorithms, developed for use with the O_2 A-band. For this, SACURA cloud data products are expected to yield the more accurate cloud parameters (although a reduced speed of the retrieval) as compared to the FRESCO.

The letter is organized as follows. In the next section, we give a brief account of the theory behind the retrieval technique. Derived results and the comparison with ground-based millimeter radar measurements are presented in Section III.

II. Theory

SACURA is based on the approximate radiative transfer in the oxygen A-band developed by Kokhanovsky and Rozanov

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A. A. Kokhanovsky is with the Institute of Environmental Physics, University of Bremen, D-28334 Bremen, Germany and also with the B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, 22072, Belarus.

V. V. Rozanov, W. von Hoyningen-Huene, H. Bovensmann, and J. P. Burrows are with the Institute of Environmental Physics, University of Bremen, D-28334 Bremen, Germany.

H. K. Baltink is with the Royal Netherlands Meteorological Institute (KNMI), 3730 AE De Bilt, The Netherlands.

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[7]. In particular, the TOA reflectance R over a cloudy scene is presented by the following equation:

$$R = R_a + T_1 R_c T_2. \tag{1}$$

Here, R_a is the reflectance of the atmospheric layer above a cloud, R_c is the cloud reflectance, T_1 is the transmission function from the sun to the cloud layer, and T_2 is equal to the light transmission on the way from the cloud to a satellite. Note that R_c also includes the effects of the surface albedo and the aerosol layer reflectance beneath the cloud. Semianalytical equations for the calculation of all functions given in (1) have been proposed in [7] and will not be discussed here.

Our retrieval algorithm is based on (1). In particular, we minimize the difference between the measured function $R_{\mathrm{mes}}(\lambda)$ and the function $R(\lambda)$ given by (1). This is possible due to a high spectral resolution of SCIAMACHY in the oxygen absorption band (58 spectral points in the narrow band 759–770 nm). The parameters to be found include cloud top height h and the cloud geometrical thickness l. The cloud optical thickness is estimated from measurements outside the oxygen absorption band (at 750 nm). Obviously, the pair (h, l) does not depend on wavelength. Therefore, the retrieval is stopped if the difference of measured spectra and those calculated using (1) reaches a minimum. Then it is assumed that we have a cloud with obtained values of the pair (h, l). We do not consider the problem of the uniquiness of the solution here. Indeed, the same TOA reflectance can be obtained using a single layer with given values of (h, l) or using a vertically inhomogeneous layer with other values of the cloud top/base height [10].

The approach introduced above can be applied to completely cloudy pixels only. However, it can be modified to account for a partial cloud cover of a given pixel. Obviously, the accuracy of the retrieval increases with the cloud fraction c. We present the top-of-atmosphere reflectance R_p for a partially cloudy pixel by the following linear combination:

$$R_p = cR + (1 - c)R_{\mathrm{atm}} \tag{2}$$

where R is given by (1) and R_{atm} is the TOA reflectance for a cloudless situation. Obviously, it follows at $c = 1$: $R_p = R$. Therefore, we can use the algorithm described above. For partially cloudy pixels, however, the situation is more complex and we need to minimize the difference δ

$$\delta = R_{\mathrm{mes}} - cR - (1 - c)R_{\mathrm{atm}}. \tag{3}$$

The problem is that neither c nor R_{atm} are known *a priori*. Therefore, we need to make some assumptions to make the retrieval possible. We assume that R_{atm} is given by the standard model often used in the atmospheric optics studies (clear atmosphere case [7]). The value of c is obtained from measurements of the reflection function outside the oxygen absorption band assuming that the cloud has the optical thickness 10 [see (2)].

Then, we minimize the difference δ assuming that the value of R is given by (1) with the cloud optical thickness equal to 10. The droplet size distribution is characterized by the Cloud C.1 model [3].

For values of R larger than those that correspond to the cloud optical thickness 10, it is assumed that the pixels are completely cloudy ($c = 1$), and the value of the cloud top height is found using a minimization procedure based on (1).

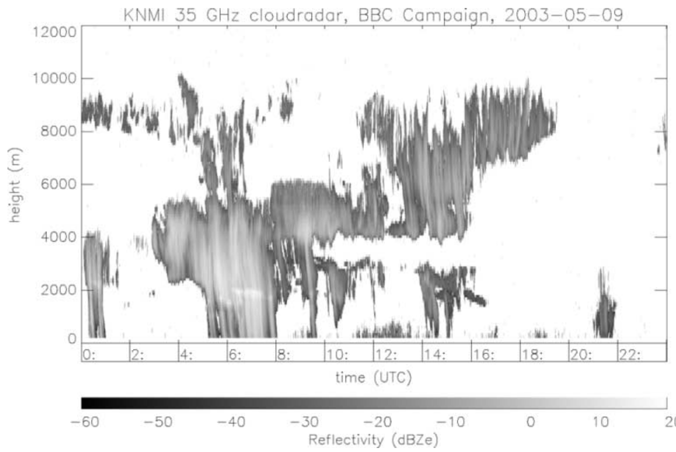

Fig. 1. The 35-GHz cloud radar backscatter data for May 9, 2003 over Cabauw.

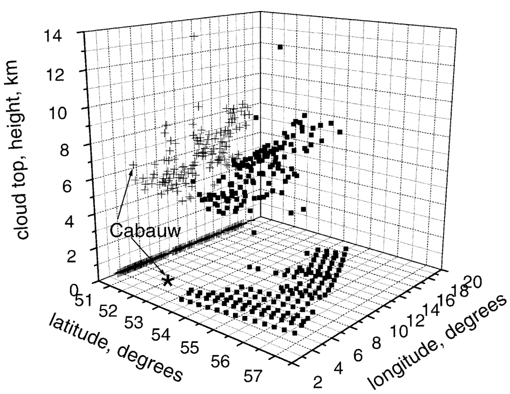

Fig. 2. Cloud top height spatial distribution derived using SACURA. Crosses show dependence on the longitude. The position of Cabauw is shown by a star. The upper arrow shows the radar-derived value of the cloud top height (6 km).

III. RESULTS

The extensive field campaign BBC-2 was performed in the Netherlands during May, 2003. In particular, combined ground-based and airborne optical and microwave measurements were carried out in the vicinity of Cabauw (51.58 N, 4.56 E). The cloud top and base altitudes were obtained during this campaign with active ground-based remote sensing measurements by millimeter radar and lidar. A characteristic example of a 35-GHz cloud radar data for May 9, 2003, is shown in Fig. 1.

SCIAMACHY measured TOA reflectance at approximately 8000 spectral points the same day above The Netherlands. Satellite measurements analyzed here were made approximately at 10:00 UTC. Therefore, data given in Fig. 1 provide an excellent opportunity for a quick check of our cloud top height retrieval technique. More thorough studies of the accuracy of SACURA will be presented in a separate publication.

We had a fortunate situation for the comparison of ground-based and satellite data on May 9, 2003, as the cloud top height over Cabauw was almost constant for about 4 h (08:00 UTC-12:00 UTC). This allows us to suggest that a large area around Cabauw was covered by an extended cloudiness located at an

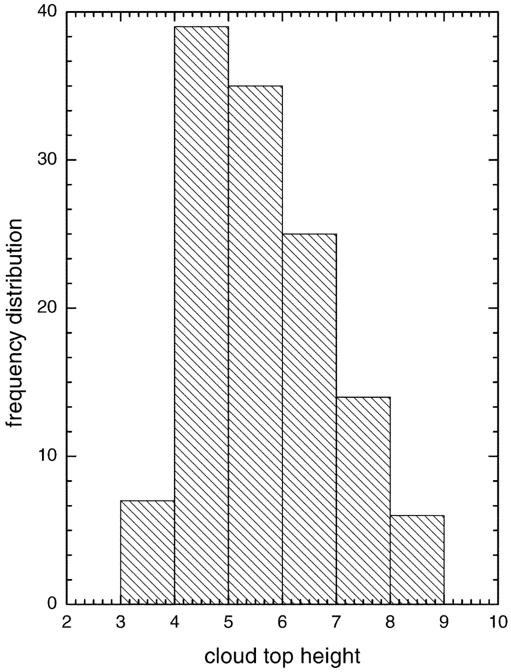

Fig. 3. Frequency distribution of the cloud top height derived using SACURA.

almost fixed height (6 km). This simplifies the comparison of radar point data with data from the SCIAMACHY, which give results averaged over large areas (approximately 1800 km^2 for a single pixel). It should be noted that that SCIAMACHY nadir views did not cover the area exactly above Cabauw on this date. Nevertheless, we believe that both the radar and SCIAMACHY observed the same moving cloud system.

Retrievals for orbit 06 217 of SCIAMACHY over an area close to the BBC-2 campaign ground measurements (May 9, 2003, $\approx$ 10:00 UTC) are shown in Fig. 2. We see that the satellite measurements are much more superior to the ground-based techniques in terms of the spatial coverage. In particular, we have derived cloud top heights for a whole orbit (not shown here). However, satellite measurements techniques are unable to give a level of detail that characteristic of ground-based measurements (see Fig. 1). Nevertheless, we can see similar features in both figures.

In particular, the radar gives the range of upper cloud top heights from 5–9 km for May 9 over Cabauw. Satellite retrievals for a much broader area give values of cloud top heights in the range 4–8 km for most of pixels at 10:00 UTC. Cloud top heights for pixels close to Cabauw are in the range 4–6 km (see Fig. 2). This corresponds well with the most probable values of the cloud top height for morning hours derived from radar measurements (see Fig. 1). The histogram of SACURA-derived values for the cloud top height is shown in Fig. 3.

The wind speed was around 65 km/h at the altitude of 5 km. This was obtained using a radiosonde and a windprofiler. The wind direction was almost constant and equal to 240° above 2-km altitude. This means that cloud fields around Cabauw propagated for the whole morning in the direction northeast. It also means that the cloud field northeast of the Cabauw site in Fig. 4 actually passed close to Cabauw earlier the same morning (between 4:00 UTC and 10:00 UTC). This is the

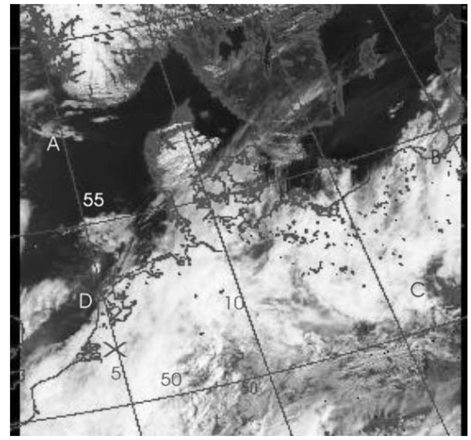

Fig. 4. MERIS on ENVISAT browse image. The resolution is approximately 1 km^2. The Cabauw site is given by a cross. Numbers give correspondent latitudes and longitudes. Letters ABCD give the position of the SCIAMACHY state analyzed (720×960 km^2). Copyright European Space Agency.

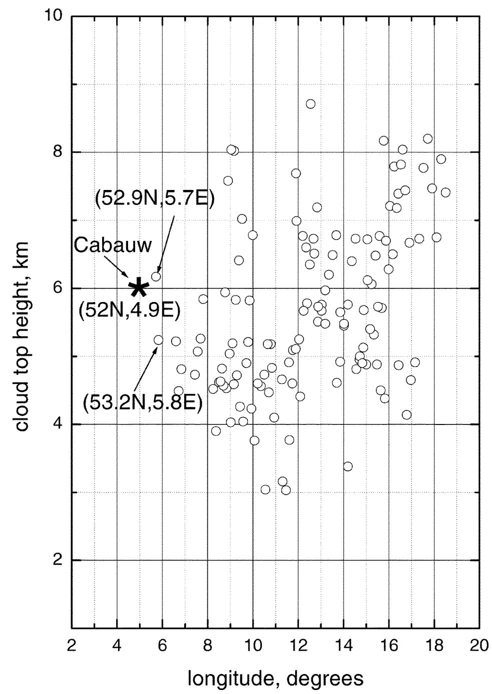

Fig. 5. Dependence of the cloud top height on longitude derived using SACURA. The data for the Cabauw site (6 km) are shown by a star.

reason for the good correspondence between radar and satellite retrievals. The SCIAMACHY looks at the same cloud field some hours after this field passed Cabauw. Pixels north of Cabauw are cloud free (see Fig. 4). The same is seen in Fig. 2.

Fig. 5 shows the dependence of cloud top height on longitude. In particular, we see that the cloud top heights for the pixels northeast of Cabauw have cloud top heights equal to 6.2 km (52.9 N, 5.7 E) and 5.2 km (53.2 N, 5.8 E). We have estimated the time clouds need to cover this distance starting from Cabauw as approximately 2 h. Thus, the retrieved clouds correspond to the cloudiness over Cabauw at a time close to 08:00 UTC. The cloud top heights were then in the range from 5–6 km (see Fig. 1).

The histogram of the cloud optical thickness distribution for the scene studied is shown in Fig. 6. Only results for thick clouds

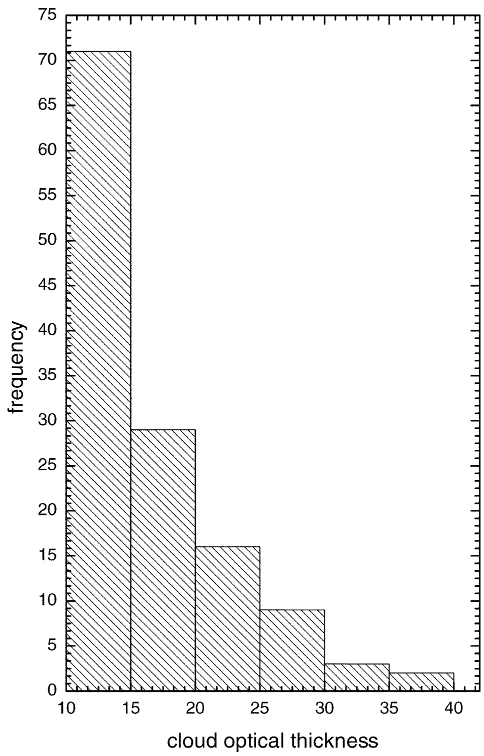

Fig. 6. Histogram of a retrieved cloud optical thickness for a scene studied.

are presented in the histogram. Results for thin clouds are not reliable due to the poor spatial resolution of SCIAMACHY. Furthermore, there is a high probability that broken cloud fields are in the field of view of the instrument. These results suggest that the cloud optical thickness is in the range from 10–40. It should be noted that Fig. 6 represents the first derivation of the cloud optical thickness for SCIAMACHY.

IV. Conclusion

The first results of the derivation of cloud top height and cloud optical thickness from the TOA reflectance measurements by SCIAMACHY in the oxygen A-band are presented. The comparison with field data shows that the developed cloud retrieval algorithm gives data close to those of ground-based millimeter cloud radar measurements. This result was obtained for a single satellite overpass. Extensive validation with ground-based measurements is required to confirm the validity of the algorithm.

Our method could be used as a complimentary technique to the infrared Advanced Along Track Scanning Radiometer (AATSR) onboard ENVISAT cloud top height retrievals. It should be noted that the accuracy of infrared techniques is usually in the range from 1–2 km [9]. Results of infrared measurements are strongly biased if high-level ice clouds are present in the field of view of the instrument. Low-level clouds also constitute a problem for infrared techniques.

The Medium Resolution Imaging Spectrometer (MERIS) instrument onboard ENVISAT is also used for cloud top height retrievals. However, MERIS measures the TOA reflectance in just one spectral channel in the oxygen A-band. This makes it difficult to derive information on the cloud geometrical thickness, which influences the radiative transfer in the oxygen absorption band.

It should be stressed that the SACURA is capable of deriving cloud geometrical thickness and cloud fraction. However, these products only have a high accuracy for vertically homogeneous clouds. This was not the case during the present measurements (see Fig. 1).

It is of considerable importance to compare the distribution given in Fig. 6 (and also that in Fig. 3) with spatially resolved data, which are routinely obtained from MERIS and AATSR instruments onboard ENVISAT. This will also allow to check the derived value of the cloud fraction c. Obviously, the synergy of data from the AATSR-MERIS-SCIAMACHY deserves a special attention. The consideration of this issue, however, is far beyond this letter.

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